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Fisheries management responses to climate change in the Baltic Sea



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ABSTRACT

The long term management plan for cod in the eastern Baltic Sea was introduced in 2007 to ensure the full reproductive capacity of cod and an economically viable fishing industry. If these goals are to be fulfilled under changing environmental conditions, a readjustment of the current management plan may be needed. Therefore, this paper investigates the economic impacts of managing the cod, sprat and herring stocks in the eastern Baltic Sea, given on-going climate change, which is known to affect cod recruitment negatively. It is shown that climate change may have severe biological and economic consequences under the current cod management plan and that the negative effects on the economic performance of the fishermen as well as on the abundance of cod can be mitigated by reducing the target fishing mortality rate of cod. These results are obtained by simulating three management scenarios in which the economic consequences of different management objectives for the fishing fleets are assessed through a dynamic multi-species and multi-fleet bio-economic assessment model that include both species interactions and climate change.

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Introduction

With the introduction of the multi-annual management plan for cod stocks in the Baltic Sea (EC, 2007), the European community aims to achieve stock levels that ensure the full reproductive capacity and the highest long term yields of cod. At the same time, EU fisheries management aims to achieve efficient fishing activities within an economically viable and competitive fisheries industry (EC, 2007). One of the measures used to obtain these goals is to gradually adjust the allowed fishing mortality rate towards a specified sustainable target level. The current long term management plan for Baltic cod was established against the background of prevailing environmental and climatic conditions, but on-going climate change may alter the predicted effects of such management plans. The implications of climate change for economic as well as biological sustainability are still uncertain for fisheries managers and climate change may have implications for decisions regarding how to regulate fisheries in the future. In the eastern Baltic Sea, climate change is expected to affect the recruitment of cod as a result of declining salinity and oxygen levels (MacKenzie et al., 2007b) and may result in a long term decline in the cod stock biomass. This will have an impact on the economic performance of fishermen who fish in the Baltic Sea. Therefore, if the goal is to maintain the economically important cod stock biomass at the current level or to maximise economic performance indicators for the fishing fleet, a readjustment of the current management plan may be needed.

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This paper presents an age-structured bio-economic model aimed at assessing the impact of climate change on the long term management of Baltic cod. Although the effect of climate change is expected to decrease the economic fleet performance as a result of reduced reproduction opportunities for cod, the expected economic loss may be reduced as a consequence of lower cod predation on sprat and herring, leading to higher production potential for these species. The model, which is outlined in Section “Method”, has been extended to include the effects of species interactions as well as climate change and is applied to the Baltic Sea fleets which target cod, sprat and herring. The long term economic (revenue, profit, net present value) and biological (stock biomass) effects of three management scenarios are presented by simulating the long term dynamics of the fishing fleets.

Economic studies of climate change in fisheries

Cod is an economically important species in the northern hemisphere and the impacts of climate change on cod have therefore been the subject of several studies (Lorentzen and Hannesson, 2005; Arnason, 2007; Eide, 2008). The economic effect of climate change on the cod fisheries in the Barents Sea was estimated by Eide (2008) and included both a cooling effect on water temperature due to the weakening of the Gulf Stream and a direct warming effect due to a warmer climate. Eide concludes that the economic effect of climate change is insignificant compared to the economic effect of normal environmental fluctuations in the Barents Sea and compared to the economic impact of different management regimes. Another study (Lorentzen and Hannesson, 2005) found that the effect of climate change on the Norwegian cod fisheries of the Barents Sea would be an increase in stock abundance of about 100,000 tonnes per year, corresponding to more than one billion Norwegian Kroner per year. The potential cooling effect resulting from a weakening of the Gulf Stream is excluded in this study.

A number of studies have been conducted into the impact of climate change on the ecosystems of the Baltic Sea (Möllmann et al., 2003; Neumann, 2010; Margonski et al., 2010; Lindegren et al., 2010; Voss et al., 2011; Meier et al., 2011; Voss et al., 2012). However, few have studied the economic effects of climate change in the Baltic Sea. Brandt and Kronbak (2010) investigated the stability of fishery agreements under climate change in the Baltic Sea using an age-structured bio-economic model. The authors used a Beverton Holt recruitment function with three different recruitment parameter values for cod, corresponding to low, medium and high impacts of climate change, to estimate the net present value over 50 years and concluded that climate change will lead to reduced reproduction, thereby reducing the likelihood of stable cooperative agreements. While the latter study was applied to one species, Nieminen et al. (2012) include cod, sprat and herring in an age-structured multi-species bio-economic model for the Baltic Sea, including interactions between different species. They assess different management scenarios and either use current fishing mortality rates or fishing mortalities that maximise the net present values, under “good” and “bad” environmental conditions respectively. The study shows large differences in net present values and fishing mortalities in the four management scenarios.

The present paper also assesses the economic impacts of management scenarios for cod, sprat and herring, and includes species interaction as well. However, the present study differs from the study by Nieminen et al. (2012) in that it includes salinity predictions from a recent climate model for the Baltic Sea (Meier et al., 2011) in the applied bio-economic model. Furthermore, the present model differs from the one used by Nieminen et al. (2012) in that it includes multiple fleet segments with detailed information regarding the cost structure, by including investment and disinvestment opportunities for the fleets and by including age-disaggregated prices.

The effect of climate change on the Baltic Sea cod

The increasing number of models that attempt to measure the main dynamics of marine ecosystems has also led to studies of the effect of a changing climate on these ecosystems and the resulting economic consequences for the fisheries (Margonski et al., 2010; Neumann, 2010; Norman-López et al., 2013). The effects of climatic change range from increasing sea surface temperatures (SSTs) and reduced ocean acidification (pH) to rising sea levels and varying frequencies and amplitudes of rainfall, storms and cyclones (Hobday et al., 2008; Bates et al., 2008). In Northern Europe, the observed volume and intensity of precipitation increased during the period 1946–1999, which has increased runoff to water bodies and the risk of flooding (Bates et al., 2008). Runoff is expected to increase by 9–22% by the 2070s (Bates et al., 2008), which will increase the discharged volume of brackish water into the Baltic Sea (Schinke and Matthäus, 1998). One of the consequences of this is reduced salinity concentrations in the Baltic Sea, which is also a result of a reduction in major saline water inflows from the North Sea through the Danish straits and the Belt Sea (Matthäus and Lass, 1995; Schinke and Matthäus, 1998; Schinke and Matthäus, 1998; Meier and Kauker, 2003; Matthäus et al., 2008; Neumann, 2010). Moreover, regional ocean models show that increasing sea surface temperatures of 2–3 °C are expected for the Baltic Sea by the end of the 21st Century (MacKenzie et al., 2007a; Meier et al., 2011), which is directly caused by air–sea interaction (Dippner et al., 2008).

The present study focuses on how climate change will affect cod recruitment and the resulting economic consequences for the fishing fleets. Therefore, the climatic effects on salinity levels are of special concern since they are found to be positively related to oxygen, which again is positively related to the success of cod recruitment (Wieland et al., 1994; Vallin et al., 1999; Koster et al., 2005). Because Baltic cod eggs are positively buoyant in saline waters and negatively buoyant in the bottom layers in fresh waters, periods with low salinity levels will mean that the cod eggs will sink to the deeper more

oxygen poor layers. Therefore, reproduction of cod depends on major Baltic inflows (MBI) (Schinke and Matthäus, 1998) of saline and oxygenated water from the North Sea mixing with the bottom layers, causing the eggs equilibrate at more oxygen rich layers of the water column of approximately 14.5 practical salinity units (PSU) (Nissling et al., 1998; Vallin et al., 1999; Koster et al., 2005). However, the frequency of the MBI has been reducing since the 1980s (Schinke and Matthäus, 1998) and was, together with high fishing mortality rates, deemed a major reason for the decline in the cod stock during the 1980s and 1990s (Koster et al., 2005).

Meier et al. (2011) simulated the effect of climate change on salinity concentration based on a global climate model (Roeckner et al., 1999) and two greenhouse gas emission scenarios (the greenhouse gas scenarios A2 and B2 used by Meier et al. (2011), which are based on assumptions regarding demographic, economic and technological developments of the world (Nakićenović, 2000)). These estimates are used in the present paper to simulate the economic consequences (revenue, profit, net present value) of climate change in the Baltic Sea.

Method

The model used to assess the economic effects of management scenarios is based on the age-structured FishrentAge model, which is an extension of the Fishrent model (Salz et al., 2011). Fishrent is a fleet based bio-economic model which includes a detailed cost and earnings structure of multiple fleets. Multiple species can be included in the model and the catches and stock biomasses of these species are age-disaggregated in the FishrentAge model. Furthermore, fish prices are disaggregated according to the age of the fish as well as the fleet segment. The model is dynamic and is able to simulate the development over time of fleets, landings, stocks and the economic performance of the fishing fleets through a set of management rules. The investment module allows the fleet segments with positive profits to invest in new vessels and fleets with negative profits to disinvest. A detailed overview of the Fishrent model can be found in Salz et al. (2011). The basis of the FishrentAge model used in the present context is simulation and maximisation of the total net present value (NPV) for the entire fishery, where the NPV is defined as:

$$NPV = NPVT + \frac{\Pi_{f,t=T}}{r} \cdot (1+r)^{-(T+1)} \quad (1)$$

where r is the discount rate and $\Pi_{f,t=T}$ is the profit in year T , which in this paper is 25. The annual profit for all future years is assumed to be the same as in year T . NPVT is the net present value over the initial 25 years. The latter is defined as:

$$NPVT = \sum_{f=1}^F \sum_{t=1}^T \Pi_{f,t} \cdot (1+r)^{-t} \quad (2)$$

where $\Pi_{f,t}$ is the profit of fleet f at year t given by:

$$\Pi_{f,t} = Rev_{f,t} - FuC_{f,t} - CC_{f,t} - FC_{f,t} - CaC_{f,t} \quad (3)$$

where $Rev_{f,t}$ is the revenue of the fleet f at year t , $FuC_{f,t}$ are the fuel costs of fleet segment f at year t , $CC_{f,t}$ are the crew costs of fleet f at time t , $FC_{f,t}$ are the fixed costs of fleet segment f at year t and where $CaC_{f,t}$ are the capital costs of fleet f at year t . For further details of the catch equation, cost equations and investment function, the reader is referred to Salz et al. (2011).

The age-structured model uses a Pope approximation (Pope, 1972) for the estimation of numbers of fish in age-disaggregated stocks, which makes it possible to include species interactions on a more detailed level than would be possible in the original Fishrent biomass model (Salz et al., 2011). Species interaction is included in the current model based on the method introduced by Heikinheimo (2011) who includes a functional response function to measure the effect of cod predation on herring and sprat. The number of herring and sprat $P_{a,t}$ eaten by one cod in age group a in year t is described by the following functional response function:

$$P_{a,t} = \frac{C_a \cdot (N_{s+h,t})^n}{(N_{s+h,t})^n + (D_{s+h})^n} \quad (4)$$

where C_a is the maximum number of herring and sprat consumed by one cod at age a in a year when the abundance of herring and sprat is at its maximum level, D_{s+h} is the half saturation constant, i.e. the size of the herring and sprat stocks when cod consumption is half of the maximum consumption, estimated to be $D_{s+h} = 260,000$ million individuals by Heikinheimo (2011). $N_{s+h,t}$ is the population size of herring h and sprat s , measured in numbers. The functional response, i.e. the consumption rate of the predator cod as a function of the density of the herring and sprat prey species, is determined by the exponent n , where $n = 1$ is a type II functional response and $n \geq 2$ is a type III functional response (Holling, 1965). $n = 2$ is used in the present context. The functional response of cod predation on sprat $P_{s,a,i,t}$, i.e. the number of sprat of age i eaten by one cod of age a in year t , is formulated as:

$$P_{s,a,i,t} = P_{a,t} \cdot \frac{w \cdot v_{s,a,i} \cdot N_{s,t}}{N_{h,t} + w \cdot N_{s,t}} \quad (5)$$

where $N_{h,t}$ is the size of the herring stock, measured in numbers, $N_{s,t}$ is the size of the sprat stock, measured in numbers and w is the preference coefficient. The preference coefficient is necessary because cod prefer to predate on sprat rather than

herring (Heikinheimo, 2011). Furthermore, the relative preference matrix $\nu_{s,a,i}$ describes the relative consumption preference of cod of age a for sprat at age i . Similarly, the functional response function of cod predation on herring is expressed by:

$$P_{h,a,i,t} = P_{a,t} \cdot \frac{\nu_{h,a,i} \cdot N_{h,t}}{N_{h,t} + w \cdot N_{s,t}} \quad (6)$$

where $P_{h,a,i,t}$ is the number of herring of age i eaten by one cod of age a at time t , measured in numbers and $\nu_{h,a,i}$ describes the relative consumption preference of cod of age a for herring of age i . The total predation mortality rate $M2_{s,t}$ of sprat caused by cod in one year is estimated as:

$$M2_{s,t} = \sum_{i=1}^8 \sum_{a=2}^{8+} \frac{N_{c,a} \cdot P_{s,a,i,t}}{N_{s,t}} \quad (7)$$

where $N_{c,a}$ is the number of cod of age $a = 2 \dots 8+$ and $8+$ is the number of cod of age 8 or above. This means that cod older than age 8 are assumed to eat the same as cod of age 8. Similarly, the total predation mortality rate $M2_{h,t}$ for herring caused by cod in one year is estimated as:

$$M2_{h,t} = \sum_{i=1}^8 \sum_{a=2}^{8+} \frac{N_{c,a} \cdot P_{h,a,i,t}}{N_{h,t}} \quad (8)$$

The Ricker recruitment function (Ricker, 1954) is used to represent the recruitment of sprat and herring:

$$R_{k,t} = SSB_{k,t-1} \cdot e^{(r1_k - r2_k SSB_{k,t-1})} \quad (9)$$

where $R_{k,t}$ is the recruitment of species k at year t , $r1_k$ and $r2_k$ are the coefficients of species k estimated on time series from 1974–2008 and $SSB_{k,t-1}$ is the spawning stock biomass of species k at time $t - 1$. However, awareness that recruitment is not only dependent on the spawning stock biomass, but also on environmental parameters, has been increasing, and Heikinheimo (2008) found that the salinity concentration is a good proxy for environmental factors that influence cod recruitment. In the present context, Heikinheimo's method is used to estimate the recruitment of cod:

$$R_{c,t} = SSB_{c,t-2} \cdot e^{r1_c - r2_c SSB_{c,t-2} + r3_c (E_t - \bar{E})} \quad (10)$$

where $R_{c,t}$ is the recruitment of age 2 cod at year t , $SSB_{c,t-2}$ is the spawning stock biomass of cod at year $t - 2$, E_t is the salinity concentration in year t and \bar{E} is the average salinity concentration during the period 1966–2008. The coefficients $r1_c$, $r2_c$ and $r3_c$ are the coefficients for cod that are estimated using non-linear regression analysis by minimising the residual sum of squares for the time period 1966–2008. The simulated salinity concentration E_{sim_t} (where $t > 2008$) used in the simulation of management scenarios is expected to be affected by climate change.

$$E_{sim_t} = \bar{E} - d \cdot t \quad (11)$$

where d is the expected yearly change in salinity concentration. The stock biomasses of cod, sprat and herring of each time period is estimated by a pope approximation that depends on the recruitment (R), the natural mortality ($M1$), the predation mortality ($M2$) and the catches. For more detailed information of the pope approximation and how it relates to the Fishrent model, see Thøgersen (2013).

The method used to evaluate the effect of proposed climate change on the multi-annual management plan for cod is as follows. First, the biological and economic effects of the multi-annual management plan for cod are simulated in the bio-economic model that allow the age-disaggregated cod stock to predate on the age-disaggregated sprat and herring stocks. This is the baseline model, which is compared with a climate change model that, besides the inclusion of species interaction, also includes the effects of climate change on cod recruitment, where the salinity level is used as a proxy for environmental forcing on cod recruitment, cf. Section “The effect of climate change on the Baltic Sea cod”. Secondly, this climate change model, which is based on the multi-annual management plan (named Scenario 1), are compared with two alternative management scenarios that both are focused on keeping the cod stock at a sustainable level given the induced climate change and species interaction.¹ The three management scenarios are:

Scenario 1: Multiannual management plan for Cod (simulation)

It follows the multiannual management plan for cod. Target fishing mortalities for sprat ($F = 0.29$) and herring (0.22) is set according to ICES (2013).

Scenario 2: Cod preservation (simulation)

The cod stock is kept above the initial SSB of 2008. This implies that the target fishing mortality rate of cod is varied such that the stock level of cod in the final year of the simulation is the same as the value in the start year. The economic performance consequences of protecting the stock in this way are assessed. Target fishing mortalities for sprat ($F = 0.29$) and herring (0.22) are kept constant, as in scenario 1.

¹ In all scenarios, it is still required that the maximum change in TAC from one year to the next is limited to 15%.

Scenario 3: NPV maximisation

The target fishing mortalities of cod, sprat and herring are varied such that the total net present value (NPV) over an infinite time period² for the Baltic fleets are maximised. The cod spawning stock biomass is kept above a limit reference point of 90,000 tons (ICES, 2005).

Data

The analyses include 10 fleet segments that all have their main fishing ground in the eastern Baltic Sea and covered 93% of the total landed value of Atlantic cod (*Gadus morhua*), European sprat (*Sprattus sprattus*) and Atlantic herring (*Clupea harengus*) in the eastern Baltic Sea in 2011. The Fleet segments are mainly selected based on the length groups, but also the gear type and the fishing region are used to define the segments. To keep the analyses to a relatively small number of segments, the 8 EU countries that surround the Baltic Sea are divided into 4 regions: (i) DEU/POL, (ii) DNK/SWE, (iii) LTU/LVA and (iv) EST/LVA, where each region is expected to have a similar fleet cost structure, but where differences in cost structure between the four regions may be significant due to historical, regulatory or social reasons. An overview of the main technical and economic characteristics of the 10 fleet segments is provided in Table 1. The fleet segments with the most sea days per year is the passive gears 0–12 m and they amount for 64% of the total sea days, but only 10% of the catch value. In comparison does the trawlers 24–40 m amount to 17% of the sea days, but 55% of the landings value.

The biological characteristics of the three species included in the model (Table 2) include the catchable stock biomass (CSB) in the first period of the simulation and the recruitment coefficients. CSB is defined as the catchable stock biomass that can be caught by fishermen, in this case the age groups 1–8 for herring and sprat and the age groups 2–8 for cod. Other characteristics include the Total Allowable Catch (TAC), which is dependent on both the CSB, the target F, the natural mortality and management rules regarding the annual magnitude of change, see Salz et al. (2011). Furthermore, the average landings prices are presented in Table 2. Age-class specific characteristics of the model include weight at age, maturity at age, natural mortality rate and the initial stock abundance of the species all of which are presented in Table 3.

Salinity concentration from 1966–2009 was obtained from the Swedish Oceanographic Data Centre (SHARK) at the Swedish Meteorological and Hydrological Institute. The salinity measurements from station BY31 in the Landsort Deep were used as a proxy for the environmental conditions in the Baltic Sea by Heikinheimo (2008). However, this method is criticised by Margonski et al. (2010) who points out that there is no record of substantial cod spawning in the Landsort Deep. Thus, the average values of the salinity concentration from station BY5 (Bornholm Deep), which are the most important cod spawning area in the Baltic Sea, are used in the present context as a proxy for the environmental conditions in the Baltic. The average salinity concentrations (10.15 g/kg) from April to August at depth 10, 20, 30, 40, 50, 60, 70 and 80 m were used in the stock-recruitment estimation of cod. This period corresponds to the spawning peak of cod, which varied substantially between the end of April to the end July during the period 1969–1996 (Wieland et al., 2000) and in July/August in the period 1992–2005 (Bleil et al., 2009).

The development in spawning stock biomass, salinity concentration and cod recruitment during the period 1966–2010 is shown in Fig. 1. Since the cod recruits are measured at an age of 2, the time series of cod recruitment is lagged with 2 years in order to show the direct correlation between SSB, salinity and cod at the egg stage. It is here assumed that the same proportion of cod eggs survive to the age of 2 during the period. Overall, the development in spawning stock biomass is following the same trend as the cod recruitment. A visual investigation of the salinity data in Fig. 1 shows a cyclical development, where at least three periods show a clear downward sloping trend (1983–92, 1993–2002, and 2003–2010). Before these periods similar trends could be identified but not as profound. The average PSU for 1966–81 was 10.26, while it was 10.09 for 1983–2010. Although the relationship between salinity and recruitment is not obvious it could be argued that the few years with high salinity is not enough to secure recovery of the cod stock taking high fishing mortality rates into account. Furthermore, there is a distinct correlation that periods with very low salinity concentration decreases cod recruitment significantly, indicating the impact of oxygen depletion on cod recruitment. In periods with higher amount of salinity, the correlation between salinity and cod recruitment is less distinct.

Nevertheless, the expected future decrease in the salinity level is predicted by Meier et al. (2011) to be 3.2 PSU and 3.4 PSU respectively at the end of the 21st century using 2 greenhouse gas emissions scenarios A2 and B2 (see Nakićenović, 2000) as input in the global climate model, ECHAM4 (see Roeckner et al., 1999). The average of these two climate change estimates (3.3 PSU) is in the present context used to simulate the economic consequences of climate change in the Baltic Sea, where it is assumed that the salinity content of the Baltic Sea declines gradually over the period, corresponding to 0.04 PSU per year.

The functional response for each age-class of cod on sprat and herring (Eqs. (5) and (6)) includes a preference coefficient ($w = 2$), which means that cod consume two sprats for each herring (Heikinheimo, 2011). Furthermore, a relative preference coefficient matrix $\nu_{a,i}$, which determines that cod have different predation preferences for different age groups of sprat and herring respectively, is included in Eqs. (5) and (6). This is estimated based on the diet composition matrix presented by Tomczak et al. (2012).

² The yearly profit that follows after the 25 year long simulation period is assumed to be the same as the profit at year 25 (see Section “Data”). The discount rate used in the application is 3.5%.

Table 1

The main fleet characteristics for 2009–2011.

Length	Gear type	Region	Vessels (numbers)	Effort (sea days)	Landings value (million Euro)	Value share (%)
0–12 m	Passive gear	DEU/POL	473	40,649	10.1	7
	Passive gear	DNK/SWE	445	23,568	4.2	3
12–24 m	Trawl and seine	DEU/POL	63	7,548	10.6	7
	Trawl and seine	DNK/SWE	43	6,479	17.8	13
	Trawl and seine	EST/FIN	57	2,534	4.2	3
24–40 m	Trawl and seine	DEU/POL	43	7,374	20.6	14
	Trawl and seine	DNK/SWE	22	2,842	14.9	10
	Trawl and seine	EST/FIN	26	5,306	24.0	17
	Trawl and seine	LTU/LVA	70	1,759	19.0	13
>40 m	Trawl and seine	DNK/SWE	13	2,074	16.8	12

Source: STECF (2013).

Table 2

Biological, technical and economic input values and coefficients used in the age-structured Fishrent model.

Species	TAC ^a (tonnes, 2012)	CSB ^b (tonnes, 2012)	Landings price ^c (Euro/kg, 2009–2011)	Recruitment coefficient ^d		
				r1	r2	r3
Cod	67,850	232,791	1.02	0.50	1.70×10^{-6}	0.24
Sprat	225,237	1,035,443	0.17	4.51	0.38×10^{-7}	
Herring	78,417	1,515,844	0.27	3.47	0.64×10^{-7}	

Sources: ^a(EC, 2012); ^bBased on ICES (2013); ^c(STECF, 2013); ^dOwn estimation, based on ICES (2013).**Table 3**

Biological age-dependent parameters from 2012.

Age	Weight at age (kg)			Maturity at age			Natural mortality rate			Stock biomass (millions)		
	Cod	Sprat	Herring	Cod	Sprat	Herring	Cod	Sprat	Herring	Cod	Sprat	Herring
1		0.006	0.014		0.17	0.00		0.45	0.33		102,580	19,971
2	0.178	0.009	0.029	0.13	0.93	0.70	0.20	0.45	0.33	209	45,026	5,759
3	0.362	0.011	0.027	0.36	1.00	0.90	0.20	0.45	0.33	145	13,853	5,881
4	0.727	0.011	0.033	0.83	1.00	1.00	0.20	0.44	0.33	77	32,221	5,781
5	0.832	0.012	0.042	0.94	1.00	1.00	0.20	0.43	0.32	39	6,696	4,660
6	1.073	0.012	0.046	0.96	1.00	1.00	0.20	0.43	0.32	22	4,359	1,717
7	1.589	0.012	0.051	0.96	1.00	1.00	0.20	0.42	0.30	10	1,408	1,123
8	2.349	0.012	0.060	0.98	1.00	1.00	0.20	0.42	0.31	6	2,028	1,451

Source: ICES WGBFAS report (ICES, 2013).

Results

The multi-annual management plan for cod, demands that the target fishing mortality rate for cod is 0.3. Moreover, the maximum change in cod TAC from one year to the next is restricted to 15%. There exists no multi-annual management plans for sprat or herring in the Baltic Sea. Instead, the target fishing mortalities estimated by ICES (2013) are used in the present context ($F = 0.29$ for sprat and $F = 0.22$ for herring).

Thus the multi-annual management plan for cod, also denoted the “EU cod plan”, is used as a starting point when assessing the economic as well as the biological implications of changing the management regimes, while acknowledging that climate change is expected to change the recruitment viability of cod and that cod predated on sprat and herring. The effect of including climate change on the long term economic fleet performance is shown in Table 4.

The present value of the economic performance indicators, revenue, variable costs, gross cash flow, capital costs and profit all show the same trend, i.e. that the climate change model results in lower performance than the baseline model obtains the lowest fleet performance, while the baseline model obtains the highest fleet performance. This result is caused by the climate change effect that has a negative effect on the long term cod stock biomass (Fig. 2).

The negative economic effect of climate change is reduced by the relative increase of the sprat and herring stocks (and thus catches and revenues) that is caused by lower cod predation on herring and sprat.

As described in Section “The effect of climate change on the Baltic Sea cod”, climate change effects the salinity concentration. Moreover, salinity is a good indicator for cod recruitment. The relationship between the expected development in salinity concentration and cod recruitment is shown in Fig. 3. As the salinity concentration declines, the cod recruitment

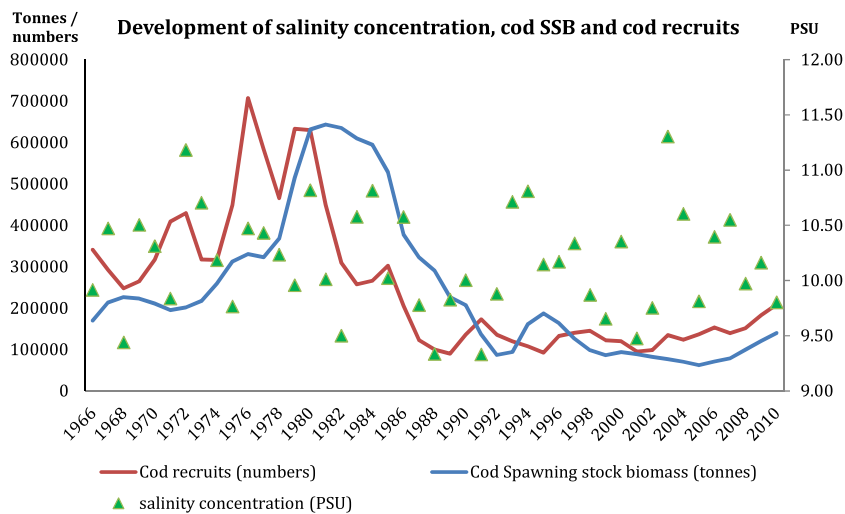


Fig. 1. Development of salinity concentration (PSU) in the Bornholm Deep, spawning stock biomass (SSB) of cod (ICES, 2013) and recruitment of cod during the period 1966–2010 (ICES, 2013).

Table 4

Present value (€ million) of economic performance indicators of the Baltic Sea fleet for the baseline model and the climate change model.

	Revenue	Variable costs	Gross cash flow	Capital costs	Profit (NPV)
Baseline model	5,092	4,181	911	493	418
Climate change model	4,511	3,673	838	447	391

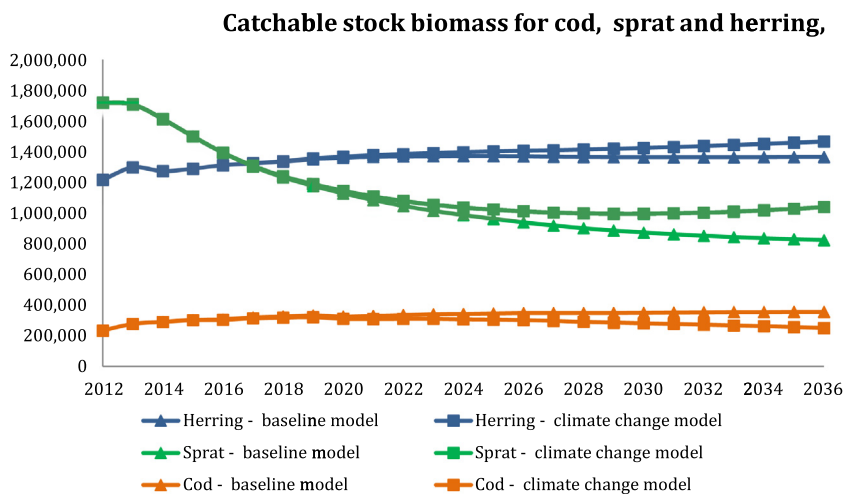


Fig. 2. The decrease in catchable stock biomass (tonnes) of cod, sprat and herring during the simulation period 2012–2036 for the baseline bio-economic model including species interaction and bio-economic model that includes the effect of climate change.

does the same. The recruitment of cod in the beginning varies. This is because it is based on the most recent recruitment estimates (ICES, 2013). This reflects well the stochasticity that is expected in both the salinity concentration and the cod recruitment over the entire period. However, since the purpose of this paper is to describe the overall trend of the recruitment, stochasticity is not dealt with for the long term simulation.

Given the above analysis, it is clear that climate change will alter the expected economic and biological outcomes of the multi-annual management plan for eastern Baltic cod to some extent. Therefore, it is important to discuss alternative management strategies that can maintain the cod stock within sustainable limits while ensuring an economic outcome which is as high as possible for the fishery. Table 5 shows the present value of profit (NPV) for the Baltic fleet for three management scenarios, all evaluated based on both the baseline model and the climate change model. Scenario 1 is assumed to follow the management plan for cod and corresponds to the NPV of Table 4. Scenario 2 is based on cod preservation, where the cod

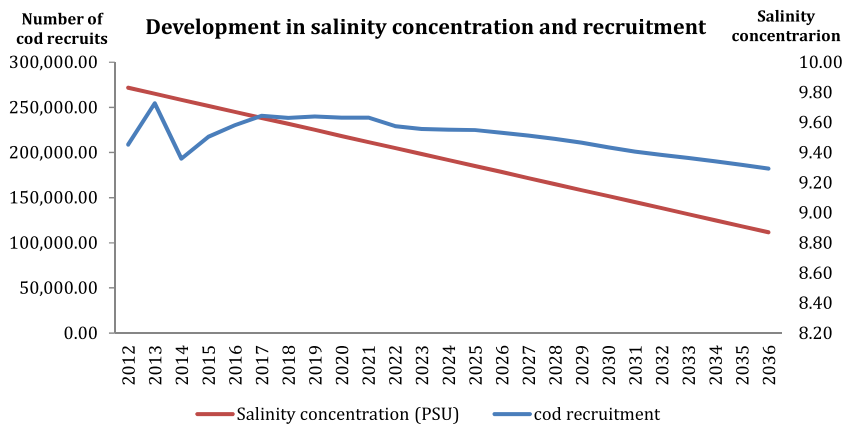


Fig. 3. The expected development in the salinity concentration (practical Salinity Units, PSU) and cod recruitment (numbers) in the period 2012–2036.

Table 5

Present value of profit (€ million) for the three management scenarios as well as the percentage change in scenario 2 and 3 relative to scenario 1.

	Scenario 1 EU cod plan	Scenario 2 cod preservation		Scenario 3 maximise NPV	
	€ million	€ million	Relative change (%)	€ million	Relative change (%)
NPV – baseline model	418	421	1	474	13
NPV – climate change model	391	406	4	472	21

stock is maintained above the 2013 level and Scenario 3 maximises the NPV by adjusting the fishing mortality with the constraint that all stocks are above the minimum viable stock level. Under the baseline model, the simulated NPV of the fishing fleets, obtained in the cod preservation scenario, is approximately the same as under the cod management plan as a result of a fairly stable development in the cod stock, while the NPV maximisation scenario is increased by 13% in the NPV maximisation scenario by reducing the fishing mortality of cod and increasing the fishing mortality of herring and sprat.

Under the climate change model, the NPV will increase with 4% relative to scenario 1, because the conservation strategy will mitigate the pressure on the cod stock. This means that increasing the cod stock under climate change by lowering the target fishing mortality for cod will have a positive influence on the economic performance of the Baltic Sea fleets. In the NPV maximisation scenario, the NPV is increased by 21% by reducing the fishing mortality of cod even further and by increasing the fishing mortality of herring and sprat. The effects of the NPV maximisation scenario through reallocation of fishing mortality will thereby be positive regardless of climate change, but the need for such management plan will be significantly larger with climate change.

The development in the revenue over the entire simulation period is shown in Fig. 4 for both the baseline model (lower part of the figure) and the climate change model (upper part of the figure). Following the EU management plan for cod (Scenario 1) in the climate change model, the revenue of the entire eastern Baltic fleet is expected to decrease to €145 million in 2036 as a result of climate change, whereas the cod preservation management scenario will lead to slightly higher revenue. Scenario 3 increases the generated revenue until year 2026 and is then reduced, partly because of climate change and partly because the revenues and profits in the beginning of the period contribute more to the NPV than later, due to discounting. This results in a NPV at €472 million. In the baseline model, the development in revenue is relatively stable for Scenario 1 and 2, while the revenue in scenario 3 decreases initially, after which it increases to €205 million in 2036.

The fishing mortalities that lead to the above dynamics are shown in Table 6. The target fishing mortality rates that are used in scenario 1 are the same as those used in the multi-annual management plan for cod and for the Baltic Fisheries Assessment Working Group (ICES, 2013). Through optimisation, scenario 2 finds the target fishing mortality rate that preserves the cod stock. This is estimated to be 0.31 for the baseline model and 0.28 for the climate change model. The target F of cod that maximises the NPV declines to 0.21 for both models, compared to the 0.3 used in the EU cod plan, while the target F for sprat and herring increases to 0.37 and 0.46 for the baseline model and 0.33 and 0.38 for the climate change model, compared to 0.29 and 0.22, used by ICES (2013). It is worth noting that in scenario 3 where the model is allowed to estimate all F 's, the target fishing mortality for herring and sprat is higher than the $MSY-F$ for these stocks estimated on a single stock basis. Furthermore, these target F 's are lower in the climate change model compared to the baseline model. This reason for this is that the increase in stock sizes reduces the recruitment rate as a Ricker stock-recruitment relationship is assumed. Hence, lower target fishing mortality rates are required to maximise NPV in the climate case than in the baseline case.

It is clear from Table 6 that the target fishing mortality rate for cod must be reduced significantly in order to maximise the net present value of the fishing fleets. If the purpose is to preserve the cod as in scenario 2, the fishing mortality rate of cod must also be reduced if climate change is taken into account.

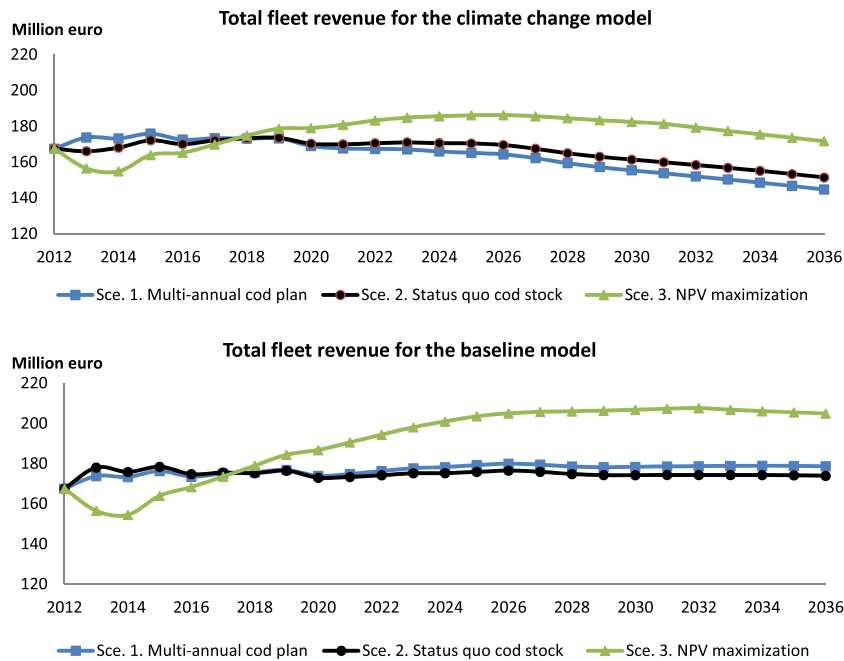


Fig. 4. The development in total fleet revenue (€ million) in the period 2012–2036 for the three management scenarios. The upper part shows the climate change model, while the lower part shows the baseline model.

Table 6

Target fishing mortality rates (Target F) used/obtained in different management scenarios.

Management scenarios	Baseline model			Climate change model		
	Cod	Sprat	Herring	Cod	Sprat	Herring
Scenario 1: EU cod plan	0.30	0.29	0.22	0.30	0.29	0.22
Scenario 2: cod preservation	0.31	0.29	0.22	0.28	0.29	0.22
Scenario 3: maximise NPV	0.21	0.37	0.46	0.21	0.33	0.38

The stock development for cod, sprat and herring is given in Fig. 5 for scenarios 1–3. Following the EU cod plan, the model predicts that the cod stock will decline from year 2019 due to climate change, but it will still be above the limit reference points³ for cod in 2036. The cod stock development of the cod preservation scenario is slightly higher and reaches 296,000 tonnes in 2036. If the purpose is to maximise the long term profits of the fishing fleet (Scenario 3), the stock biomass should be allowed to increase to 485,000 tonnes until year 2026 by initially lowering the catches of cod and then slowly increasing the catches. The cod stock is then reduced to 436,000 tonnes in year 2036 due to a combination of high catches and climate change effects.

The sprat stock decreases rapidly in the beginning of the simulation period (cf. Fig. 5) for all management scenarios, in order to reach the MSY biomass level, in accordance with ICES (2013). Compared to multi-annual cod plan, the sprat stock decreases both slightly in scenario 2 and scenario 3, because the increasing cod stock in scenario 2 and 3 induce higher predation on the sprat stock. The herring stock biomass is expected to increase slightly for both the cod management plan as well as for the cod preservation scenario. Similar to the sprat stock, the herring stock is also expected to decrease due to increased cod predation.

Conclusion and discussion

In this paper, the expected economic consequences of climate change in the Eastern Baltic Sea have been investigated in a dynamic age-structured bio-economic model that takes species interactions into account. Through three management scenarios, representing different management objectives, the paper analysed how a manager could react to these changes. The effects of the management scenarios are also shown for the baseline model, which does not include the effects of climate change. The management scenario that follows the multi-annual management plan for cod in the Eastern Baltic Sea shows

³ A limit reference point of 90,000 tons is suggested (ICES, 2005).

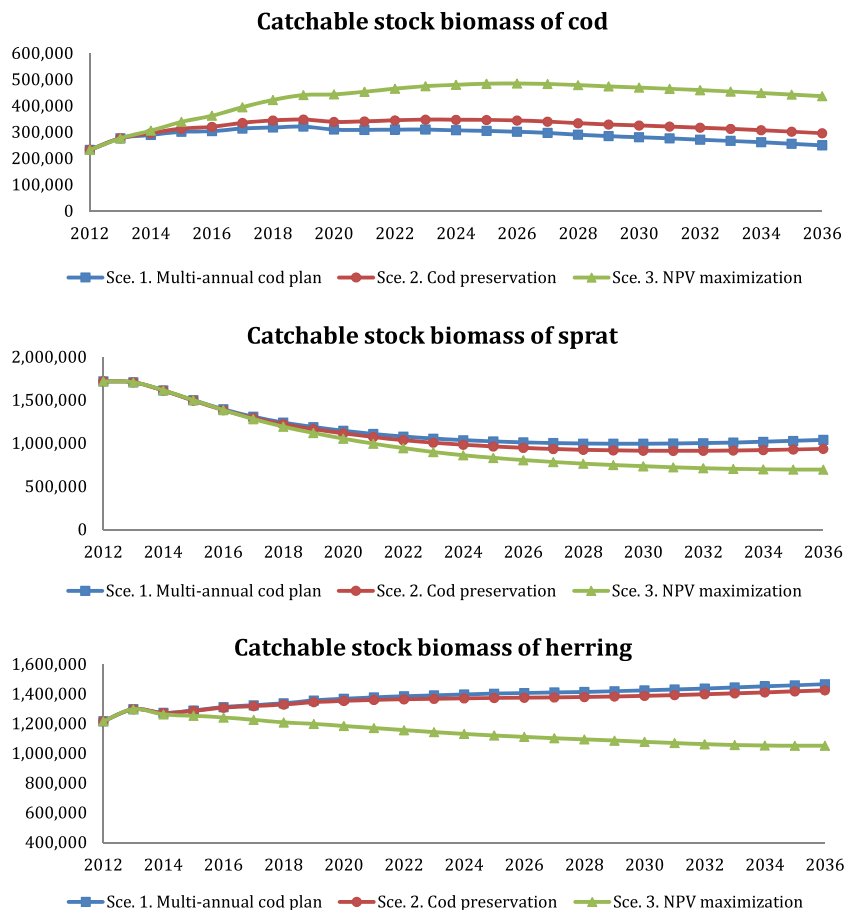


Fig. 5. The development (tonnes) in catchable stock biomass (CSB) for cod (upper graph), sprat (middle graph) and herring (lower graph) in the climate change model. In each graph, the development of CSB for three management scenarios is presented in the period 2012–2036.

that climate predictions have a negative effect on the net present values of the fishing fleets. The cod stock is affected negatively by the predicted climate change, leading to lower biomass levels at the end of the simulation period (year 2036). Preserving the cod stock, as done by management scenario 2 by lowering the target fishing mortality rate of cod, leads to higher net present values of the fishing fleets as well as higher cod stock levels compared to the baseline scenario. The last management scenario maximises the net present value of the fishing fleets by optimising the target fishing mortality rate, which results in reduced target fishing mortality rate for cod and increased target fishing mortality rate for sprat and herring, compared to the baseline scenario. The last management scenario shows that if the purpose is to maximise the net present values of the fishermen, the current target fishing mortality rate of cod should be reduced and the current fishing mortality of herring and sprat should be increased. This point is true irrespective of climate change, but the economic gains from such a management scenario are significantly higher in the climate change model, compared to the baseline model. Compared to the multi-annual cod management plan, the implementation of target fishing mortalities that maximise the long term net present value for the fishing fleets must be expected to favour the fleet segments which target cod, since the relative cod stock increases compared to the multi-annual management plan, which affects the relative stock of sprat and herring negatively. Economic policy analyses usually do not consider economic distributional effects among fishermen. However, the use of a numerical dynamic simulation model makes it possible to present results disaggregated into regions, fleet segments and fish stocks, which serves to enlighten the decision making process.

In the present context, salinity is only included as a proxy for the environmental effects on cod recruitment, while no climate effects are included for sprat and herring. Sea surface temperatures and/or salinity levels could have been included as environmental drivers for sprat and herring (Baumann et al., 2006; Margonski et al., 2010), but it was decided not to as too many opposing environmental factors make it difficult to interpret the results. Therefore, this paper is restricted to the effect of salinity concentration on cod recruitment, while the effect of including other environmental variables is the subject of future work.

The results presented in this paper are subject to uncertainties on different scales. On the larger scale, the results are subject to uncertainties in the two climate change scenarios that form the basis for the global climate models, predicting the future salinity concentration. The climate change scenarios are based on expected demographical, economic and

technological developments and are uncertain (Nakićenović, 2000). However, a global climate model from a recently published paper (Meier et al., 2011) did not predict significant disparities in the estimated concentration of salinity in the Baltic Sea when two different climate change scenarios were considered. The average salinity concentration of these two scenarios has therefore been used in the present context, thus catching the noise of the study by Meier et al. (2011). The relationship between salinity and cod recruitment is widely acknowledged (Wieland et al., 1994; Vallin et al., 1999; Koster et al., 2005) and has been used in several studies (Heikinheimo, 2008; Margonski et al., 2010; Heikinheimo, 2011), but the magnitude of this relationship is uncertain and depends on the chosen time series. In this paper, the entire time period from 1966–2008 for cod and 1974–2008 for sprat and herring is chosen to take account of both good and poor environmental periods. Furthermore, uncertainties will also exist in the biological data used for stock estimations and in economic data used in the bio-economic model. The results are therefore indicative and further empirical studies are recommended to support the results.

This study suggests that long term management plans should include the effects of climate change, if the aim is to secure the future long term economic performance of the fleets, while maintaining sustainable stocks in the eastern Baltic Sea. Furthermore, the study indicates that target fishing mortality rates should be lowered for cod and increased for sprat and herring in order to optimise the economic performance of the fleets, regardless of climate change. As such the study yields valuable information for the future management of the eastern Baltic Sea fishery, given that it is today an acknowledged fact that climate will change in the future, and thus affect the recruitment of, among others, the eastern Baltic cod. The study suggests that the currently accepted long-term management plan for cod may not be optimal, given the proposed climate changes, and suggests alternative management scenarios, thus also proposing a valuable tool for management assessments given climate change.

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